

Assessment of Light Duty Diesel After-Treatment Technology Targeting Beyond Euro 6d Emissions Levels

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ABSTRACT

Since previous publications, Ricardo have continued to investigate the development of advanced after-treatment technologies through model based system simulation using an integrated model based development (IMBD) approach. This paper presents the results of the evaluation of after-treatment systems and management strategies for a range of diesel passenger cars. The targets of this study are applicable to Real Driving Emissions (RDE) legislation, but now targeting emissions levels beyond Euro 6d. The work was carried out as part of the EC Horizon 2020 co-funded REWARD (Real World Advanced technologies for Diesel engines) project. Owing to the wide variation in feed-gas properties expected over an RDE cycle, the results seen for current production system architectures such as Lean NO_x traps (LNT) or actively dosed Selective Catalytic Reduction (aSCR) systems highlight the challenge to adhere to emissions limitations for RDE legislation whilst fulfilling stringent CO₂ targets. Optimisation of both the after-treatment system configuration and control strategies are required. Vehicle simulation has been performed with a range of after-treatment system specifications and engine-out feed-gas properties. The work includes an assessment of exhaust thermal management with regards to catalyst performance. The results are evaluated considering a range of criteria including; emissions control capability, estimated system on-cost, packaging limitations, fuel consumption penalty and additional fluid consumption. After-treatment system recommendations are made that deliver appropriate emissions control for a range of legislative, RDE and urban cycles for a selection of light duty diesel applications.

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INTRODUCTION

The European Union is introducing Real Driving Emissions (RDE) legislation with the aim to ensure real world and urban NO_x emissions reduction. The first step within this legislation is expected in September 2017 [1].

Vehicles are required to achieve type-approval for a particular NO_x level and also comply within an emissions Conformity Factor (CF) during normal driving conditions. It is clear that the reduction of NO_x over a greater range of engine operating conditions is required compared to current legislation and therefore, it is essential to understand the impact of this requirement on the diesel powertrain (including after-treatment system) for technology development to meet future emissions legislation steps.

Project REWARD

The REWARD project is a co-funded collaborative research project as part of the Horizon 2020 (H2020) Programme, which itself is drawn from the EU Framework for Research and Innovation. The overall objective of the REWARD project is to improve the efficiency of current diesel powertrains and after-treatment technologies for a range of passenger car classifications, with emissions capability beyond Euro 6d limits under real driving conditions [2].

This paper details the simulation assessment of future after-treatment systems to define those capable of enabling a future diesel powertrain to achieve the REWARD project emissions targets (detailed in [table 1](#)). To achieve this, multiple after-treatment approaches have been evaluated for a range of vehicles over drive cycles representative of real driving conditions. For NO_x emissions an RDE cycle conformity factor (CF) of 1.5 was applied, resulting in an absolute target of 60 mg/km.

Table 1. REWARD project emissions targets compared to current Euro 6d limits

Emissions	Euro 6d	REWARD
CO [mg/km]	500	250
HC + NO _x [mg/km]	175	85
NO _x [mg/km]	80	40
PM [mg/km]	5	2.5
Pn [# /km]	6.0 x 10 ¹¹	3.0 x 10¹¹

Under the over-arching objective, further aims of this study were to:

- Understand the limitations of current Euro 6 after-treatment solutions to meet emissions conformity in real world driving
- Evaluate the sensitivity of after-treatment properties and calibration to emissions conformity capability
- Define a range of after-treatment systems suitable, considering emissions control capability, estimated system on-cost, packaging limitations, fuel consumption penalty and additional fluid consumption.

APPROACH

The approach chosen was to use a sub-set of the Ricardo Integrated Model Based Development (IMBD) environment and simplified tools to provide a faster than real time evaluation, therefore enabling system optimisation over the large input matrix of input conditions. The block diagram of the IMBD environment for the simulations is shown below in [figure 1](#).

With this method, the likely success or failure of a specific technical solution can be reviewed before committing to a costly development programme. This approach, frequently utilised by Ricardo and reported in previous work [3] [4], has been shown to enable fast adaptation to varying inputs and system properties.

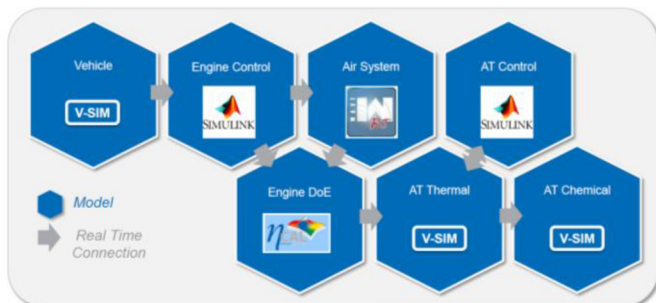


Figure 1. Sub-set of Ricardo Integrated Model Based Development (IMBD) environment used for after-treatment simulation

System Modelling

To provide after-treatment recommendations, the entire application (vehicle, drivetrain, engine and after-treatment) has been simulated over relevant drive cycles (real and synthetic). The flexible approach chosen, as detailed below in block format [figure 2](#), was to develop Simulink based models of the application using Ricardo Vehicle Simulation Toolset (V-SIM).

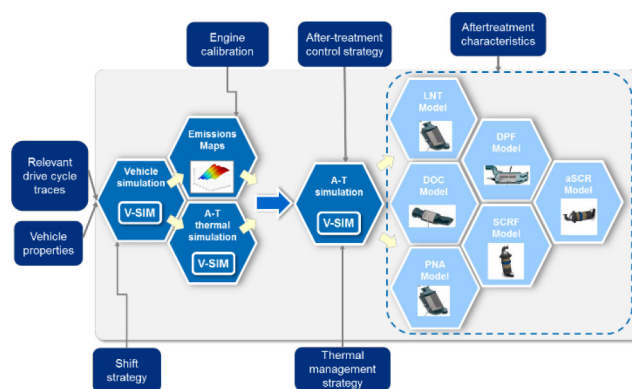


Figure 2. System modelling approach

This approach is modular and therefore adaptable to a wide range of architectures, which allows for detailed review of each sub-system and the rapid modification of various characteristics to understand the sensitivity to the final result.

Thermal Modelling

An accurate temperature profile of the after-treatment system is key to predicting emissions conversion performance. Specific temperature profiles for the wide matrix of systems, calibration settings and drives cycles were not available. An approach was therefore developed using steady-state test data and system properties to predict the exhaust feed-gas temperature profile.

To convert steady-state exhaust feed-gas temperature data, used as a model input, into a transient drive cycle feed-gas temperature profile, an additional thermal system was developed. The effect of this approach is shown in [figure 3](#). The subsequent predicted after-treatment feed-gas temperatures shows a much better match to the transient test data. The steady-state exhaust temperature map was also corrected for cold coolant temperatures to better simulate engine warm-up - this was found to be highly influential for relatively short cycles where the warm-up period is dominant.

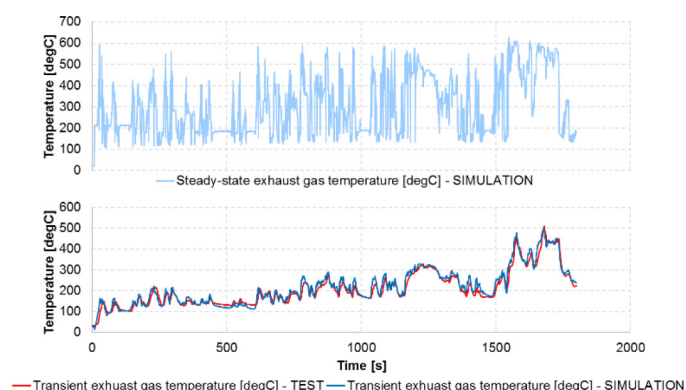


Figure 3. Effect of thermal modelling simulation - comparison to test data (top: steady-state map output, bottom: comparison of transient temperature)

For the components downstream of the engine such as the pipes, cones, canning; the physical properties were used within the thermal model to accurately predict temperatures throughout the system. For the catalysts further properties regarding the wall thickness, void fraction, CPSI, Cp and porosity were used.

Input Data

Powertrain Properties

Two applications were included in the study allowing the comparison between engine and vehicle differences, and their sensitivity to after-treatment system performance. The applications were:

- C-segment, 1.6L
- SUV, 2.0L, RS2

The engine architecture for the two applications was representative of current Euro 6 applications with dual EGR strategy. The engine out NO_x emissions for all the applications were calibrated to low values with extensive use of both low and high pressure EGR over a wide operating range. This is a required element of overall NO_x control for WLTC and RDE operation, when compared to the Euro 6 'NEDC' calibration starting point.

The vehicle mass was as prescribed for the legislative cycles. For the non-legislative cycles typical weight values for additional passengers and PEMS (portable emission measurement system) equipment were used. The gear shift strategy employed was cycle dependent; for legislative cycles the gear shift selection was prescribed, whereas for the non-legislative cycles a standard shift pattern was employed which is representative of a typical driver.

Drive Cycles

In order to develop a truly capable emissions control system to meet the REWARD project targets, a wide range of vehicle drive cycles was required encompassing all likely areas of system operation. The cycles used within the simulations can broadly be grouped under four categories;

- RDE compliant cycles
- Legislative cycles
- Urban driving cycles
- Aggressive driving cycles

A list of cycles simulated is provided in [table 2](#). A number of cycles fall outside of the RDE legislation, however, they have been considered to enable evaluation of the after-treatment system across the likely operation of the applications.

Four RDE cycles were considered and are all derived from the RS115 cycle, which is a developed cycle based upon a representative drive over a Ricardo standard RDE test route. This has been reported during previous work [3]. The route met the Ricardo understanding of the likely final legislated boundary conditions for RDE route definition at the time the simulation was taking place. To enable a wider assessment of the after-treatment systems, a further three cycles

were developed, with increasing levels of severity, allowing the evaluation of the after-treatment system under higher mass flows and temperatures.

Table 2. List of simulated drive cycles

Cycle	Length [seconds]	Category	Applicability	RDE Compliance
WLTC	1800	Legislative	Used for correlation and legislation purposes	✗
NEDC	1180		Used for correlation and legislation purposes	✗
ARTEMIS	3068	Aggressive	Used for correlation purposes	✗
RTS95	2655		High temperature and mass flow capability assessment	✗
RUK Delivery	3598	Urban	Door-to-door cycle – frequent engine off periods Used to assess low temperature capability	✗
RUK City	960		Representative of city driving Used to assess low temperature capability	✗
RS115	7160	RDE	Ricardo derived RDE cycle	✓
RA140+	6769		Manufactured cycle based on RS115 Increased severity and highway phase speed	✗/✓ (application dependent)
RA145+	6883		Manufactured cycle based on RA140+ Increased severity and highway phase speed	✗/✓ (application dependent)
RA1-140+	6769		Manufactured cycle based on RA140+ but rate of RDE compliance is higher	✓

The RA1-140+ was such a cycle and the vehicle speed profile for it, the RTS95 and the RS115 are shown in [figure 4](#). Owing to the high highway speed and gradients the compliance of the aggressive cycles with regards to 'normal' driving, considering the RDE legislation, was found to be dependent on the application.

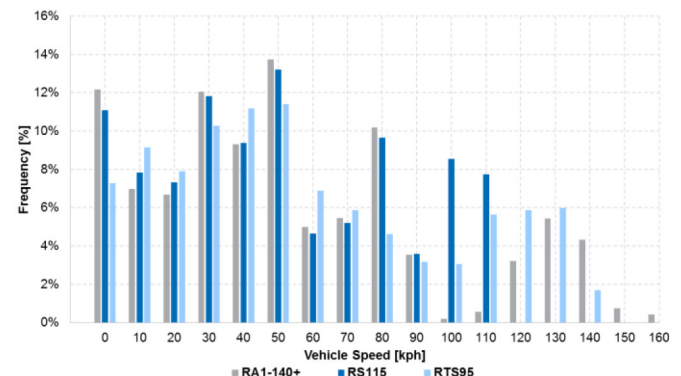


Figure 4. Vehicle speed frequency distribution comparison for RS115, RA1-140+ and RTS95 drive cycles

The vehicle velocity multiplied by positive acceleration ($V \times A_{pos}$) dynamics assessment of three cycles is shown below in figure 5. The difference between the two Ricardo defined RDE cycles highlights the increased aggressiveness of RA1-140+ cycle compared to RS115, yet still remaining within current RDE validity parameters. Figure 5 also shows a comparison to the RTS95 cycle; which lies outside of the legislated $V \times A_{pos}$ criteria for rural and highway phases, but remained of interest as a highly aggressive cycle.

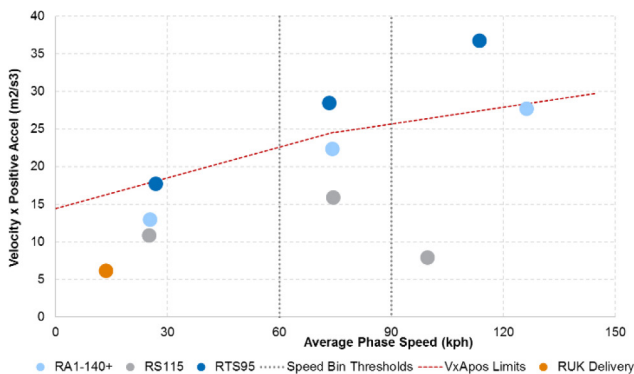


Figure 5. $V \times A_{pos}$ comparison for RS115, RA1-140 and RTS95 drive cycles

To assess the after-treatment system during urban driving conditions, a number of cycles were simulated representing city and town driving. The engine load profiles of two of these cycles are shown in figure 6. It can be seen that a large proportion of residency time occurs between 0 and 1 bar BMEP owing to frequent start-stop events and traffic.

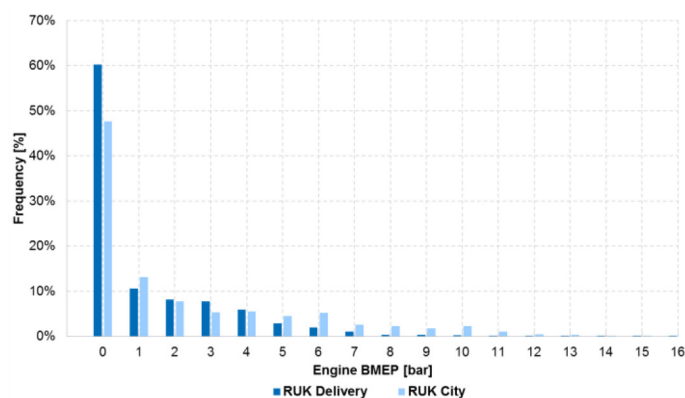


Figure 6. Engine load frequency distribution for highly urban drive cycles

After-Treatment Characteristics

The emissions-catalyst interactions within the after-treatment system were modelled based on data for the various reactions associated with each catalyst - this included both emissions species reduction or oxidation and exothermic reactions. For these simulations the data was accessed through lookup maps based on characteristic data of the latest generation of aftertreatment that was derived from synthetic gas rig and engine bench testing. The characteristics always reflected the catalysts in an aged condition.

A control strategy, representative of current production systems, was used to govern the timing of aftertreatment deNO_x events; this utilised various model parameters. The different settings were evaluated to ensure appropriate levels were set for the range of conditions investigated during the simulation.

The LNT (lean NO_x trap) model also altered the cycle fuel consumption and temperature profiles during the simulations. The effect of a purge event on fuel consumption and exhaust gas temperature uplift was modelled based on Ricardo test data. Extended purge events were applied when an LNT was used as part of a system including passive selective catalyst reduction (pSCR) in order to generate ammonia (NH₃). In these cases, an increased fuel consumption penalty for the longer duration purge events was applied. The quantity of ammonia generated, as a function of engine speed and load, catalyst temperature and purge time, was calculated from representative engine bench test data.

After-Treatment Systems Evaluated

For the C-segment applications, LNT only systems were evaluated as these do not require an AdBlue dosing infrastructure and therefore are attractive with regards to cost and complexity. LNT systems are currently in production at Euro 6 and variants of these systems were explored. From here the level of complexity and cost was increased through additional NO_x reduction catalysts and or aggressive control strategies (table 3). For the SUV application, the evaluation process started at a more aggressive after-treatment system as it was known that non AdBlue dosed systems would not perform acceptably, as detailed in previous work by Ricardo [3]. The layout of the various systems simulated, including the LP EGR route and AdBlue introduction point, are shown in figure 7.

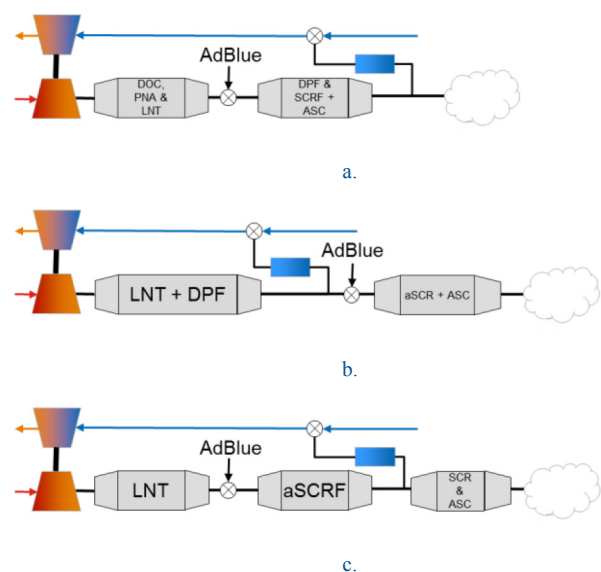


Figure 7. After-treatment system layout for the C-segment (a) and the SUV (b & c) simulations.